

The Use of Probabilistic Methods to Evaluate the Systems Impact of Component Design Improvements on Large Turbofan Engines

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Probabilistic Structural Analysis (PSA) is now commonly used for predicting the distribution of time/cycles to failure of turbine blades and other engine components. These distributions are typically based on fatigue/fracture and creep failure modes of these components. Additionally, reliability analysis is used for taking test data related to particular failure modes and calculating failure rate distributions of electronic and electromechanical components. How can these individual failure time distributions of structural, electronic and electromechanical component failure modes be effectively combined into a top level model for overall system evaluation of component upgrades, changes in maintenance intervals, or line replaceable unit (LRU) redesign?

This paper shows an example of how various probabilistic failure predictions for turbine engine components can be evaluated and combined to show their effect on overall engine performance. A generic model of a turbofan engine was modeled using various Probabilistic Risk Assessment (PRA) tools (Quantitative Risk Assessment Software (QRAS) etc.). Hypothetical PSA results for a number of structural components along with mitigation factors that would restrict the failure mode from propagating to a Loss of Mission (LOM) failure were used in the models. The output of this program includes an overall failure distribution for LOM of the system. The rank and contribution to the overall Mission Success (MS) is also given for each failure mode and each subsystem.

This application methodology demonstrates the effectiveness of PRA for assessing the performance of large turbine engines. Additionally, the effects of system changes and upgrades, the application of different maintenance intervals, inclusion of new sensor detection of faults and other upgrades were evaluated in determining overall turbine engine reliability.



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Probabilistic Methods

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Objectives

- Risk assessment of a mature system (generic).
- Quantitative probabilistic risk assessment.
- Quantitative probabilistic model development.
- Development of component data.
- Evaluating system upgrades for reducing risk.
- Conclusion



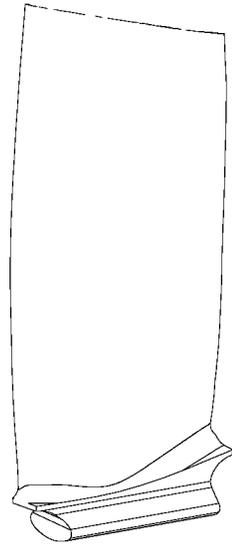
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Customer Requirements - Risks in an Uncertain World

- Risks in the component design?
- Risks in the component modeling?
- Risks in the component SW model?
- Risks in the component environment?
- Risks in the component manufacture?
- Risks in the component deployment?
- Risks in the component installation?



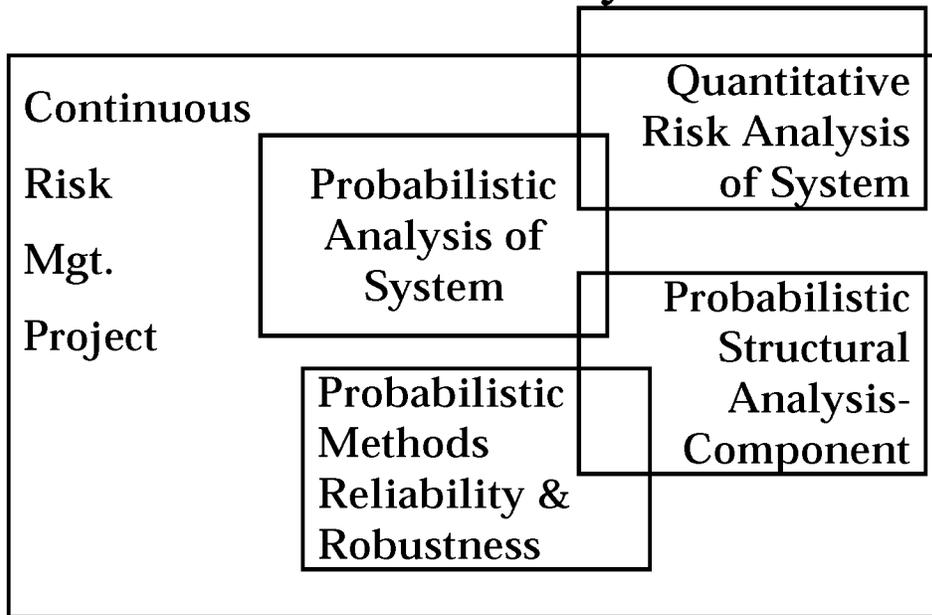


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Levels Risk of Analysis





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New Designs -- Complex Risks

- High Thrust Rocket Engines/ Aerospike
- Tiles/ Heat Shields
- Computerized Systems
- Lightweight Liquid O₂ and H₂ Tanks
- Complex System Interactions
- Integration, Payload
- Logistic Cost/On Orbit Logistics Costs

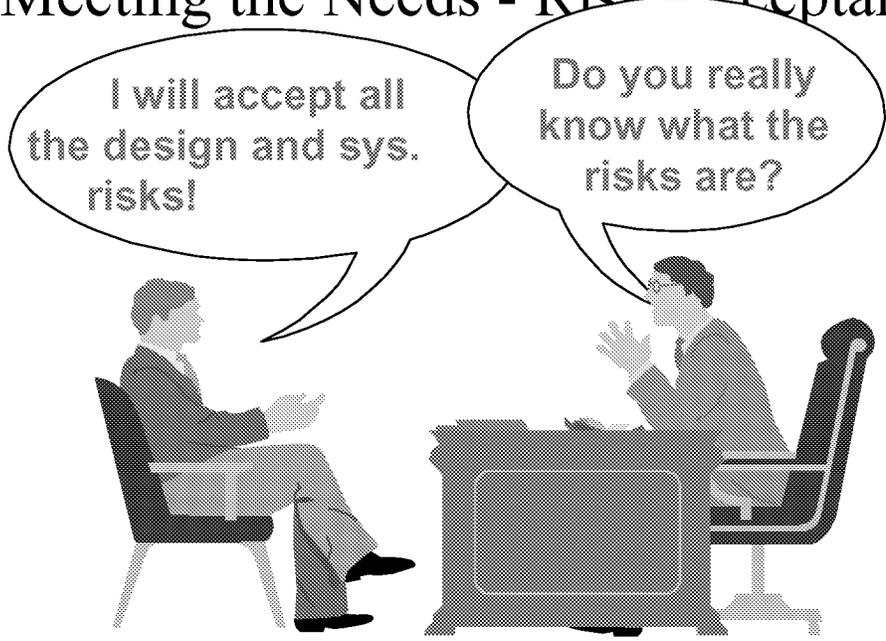


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Meeting the Needs - Risk Acceptance





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Meeting the Needs - Understanding Risks

- Product Assurance Plan
- Testing -- Number of Units
- Required Tests -- Same Lot
- Variations in Compositions
- Variations in Fabrication
- Components and Systems



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Types of Evaluation

- **Reliability Assessment** -- Usually performed on a system or component level. Objective is to determine probability of failure during a mission. Wearout also considered.
- **Probabilistic Risk Assessment** -- Goes beyond reliability and asks the question “What does the failure mean?” In addition to system/component reliability can account for other risk factors such as human error, external factors, etc.



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Basic Tools Used in Evaluations

- **Fault Trees** -- Top down evaluation of an undesirable event. Usually used in system analysis to display/quantify reliability of the system/function.
- **Event Trees** -- Also a top down evaluation, but used to string together events leading to an “end state” in a logical time ordered progression. Events considered in the event tree may be based on fault trees.
- **Reliability Assessments** -- In order to quantify model component failure modes, need failure rates.

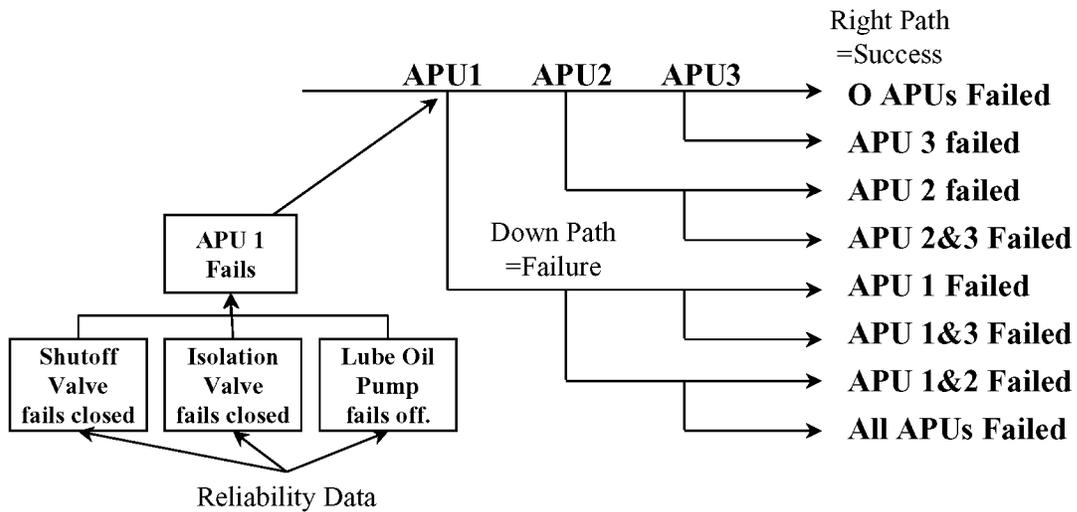


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Example: Support System Event Tree





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Background -- QRAS Description+

- Probabilistic models of subsystem failure modes based on latest available data (over time these data will be updated and improved to keep the tool current)
- Event-sequence diagrams will logically describe manner in which subsystem failure modes can lead to catastrophic failure or other end states, including the success or failure of mitigation events.



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Background--QRAS Results

- QRAS results:
 - Intermediate and or top-level model failure probabilities and their uncertainty bounds.
 - A prioritization of the “risk drivers” i.e., subsystem failure modes which are contributing the most risk to the model.
- “What if?” (or sensitivity analysis):
 - Modify the model (modifications could include replacement of subsystems with what is known or expected from proposed upgraded subsystems, additions/deletions of failure modes, changes to failure probabilities and/or to their uncertainty bounds, etc.) and re-run it to obtain changes in risk from baseline.



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Data Used in Evaluations

- Reliability Data
 - PRACA Best source, shuttle specific, least amount of data.
 - Surrogate Data -- lots of data, not system specific.
 - Expert Opinion
 - Flight Rules -- required in some cases to determine response to a failure.
- System Operations and Design -- required to understand and correctly model the system



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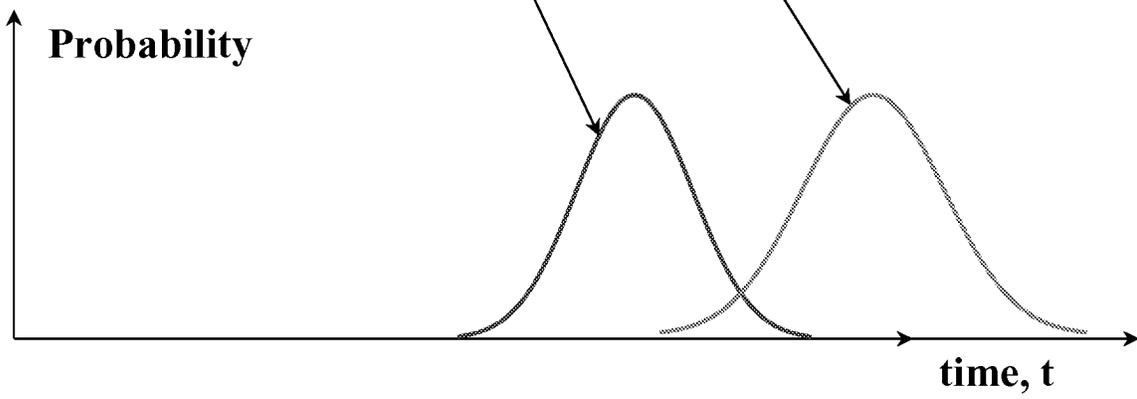
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Basic PSA--Fatigue Failure+

Based on a given duty cycle, and variations in material properties, dimensions and temperature effects the estimation of fatigue crack initiation is as follows:

Expanding on this analysis, the crack growth to a critical length or a length that can be discovered by inspection is as follows:



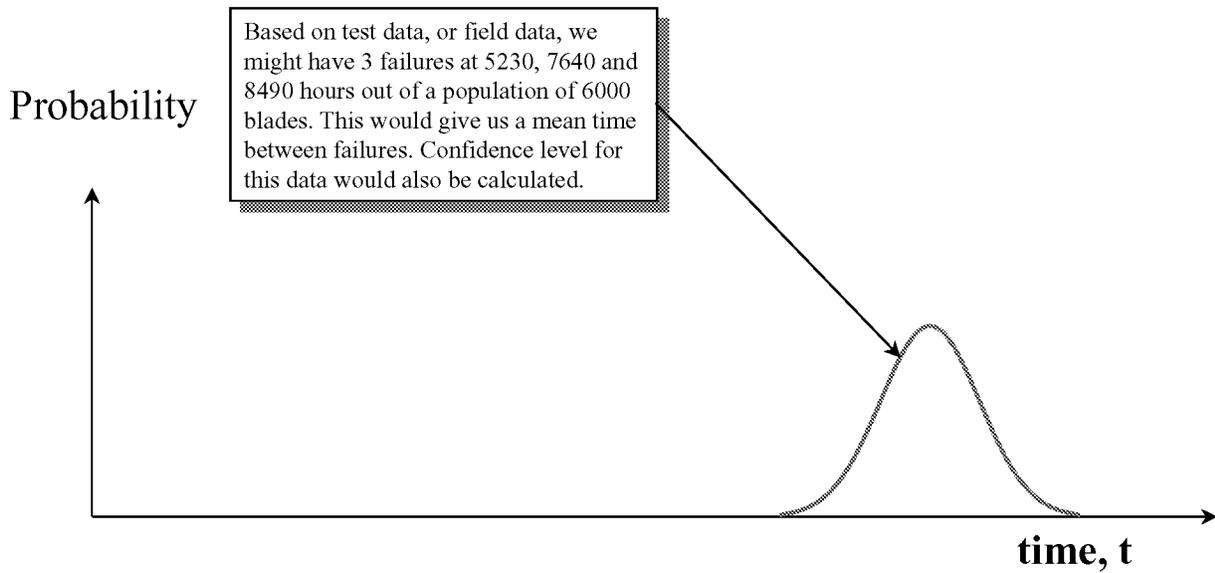


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Basic PSA -- Testing





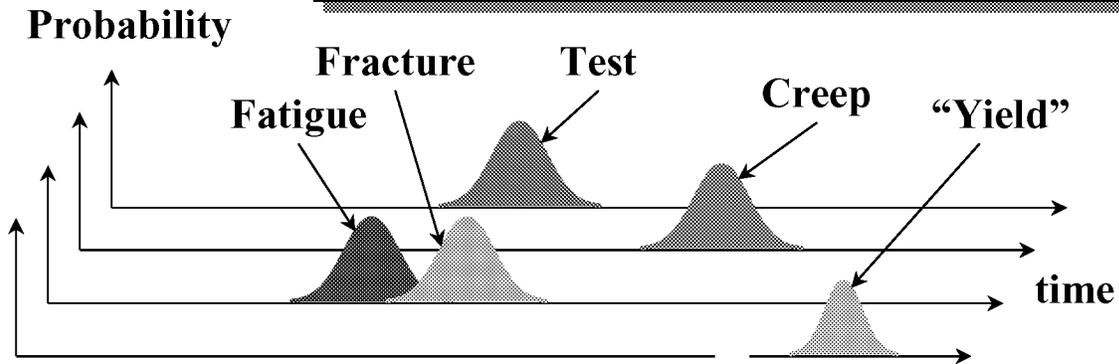
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Combining Analysis

The different failure mechanisms and failure modes may or **may not be independent or mutually exclusive**. Typically yield of a component in the time domain would be far to the right on a time line.





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QRAS Methodology

- Develop Key System Elements
- Develop Key Subsystem Components
- Develop Mission Timeline
- Develop Mission Operational Time Intervals
- Develop Failure Modes
- Develop Mitigating Events
- Develop Event Sequence Diagram



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Develop Key System Elements

- Inlet Nozzle
- Low Pressure Compressor
- High Pressure Compressor
- Combustion System
- High Pressure Turbine Module
- Low Pressure Turbine Module
- Exhaust Module
- Afterburner Module
- Fuel Module
- Auxiliary Components
- Conditioning Monitoring



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Develop Key Subsystem Components

- High Pressure Compressor
 - Compressor Rotor Assembly
 - Stage 1 Fan Disk
 - Stage 1 Blade Set
 - Front Shaft
 - No. 2 Outer Bearing
 - No. 3 Ball Bearing
 - Stage 2 Fan Disk
 - Stage 2 Blade Set
 - Stage 3 Fan Disk
 - Stage 3 Blade Set



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QRAS -- Develop Mission Timeline/OTI

- ***Idle***
- ***Take Off***
- ***Cruise***
- ***Descent***
- ***Land***
- The events are then assigned to individual failure modes once they are developed. Alternatively overall operating time may be developed.



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QRAS -- Develop Failure Modes

- High Pressure Turbine
 - Stage 2 Fan Disk
 - Turbine Blade (Stage 2) Structural Failure
 - Turbine Blade (Stage 2) Fatigue
 - Turbine Blade (Stage 2) Fracture with n Crack Length
 - Turbine Blade (Stage 2) Creep Failure
 - Turbine Blade (Stage 2) Ablation
 - Turbine Blade (Stage 2) Tip Contact



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QRAS -- Develop Mitigating Events

- Mitigating events are actions or other methods for mitigating or preventing the Failure Mode from propagating to a Loss of Mission or Catastrophic Failure.
- High Pressure Turbine
 - Stage 2 Fan Disk
 - Turbine Blade (Stage 2) Fracture with n Crack Length
 - Inspection Finds Fatigue Crack
 - Blade/Stage Changeout



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Event Sequence Diagram (ESD)

- The ESD is the basic element used to evaluate failure modes.
- The ESD evaluates the probability of a failure mode as well as mitigating events which prevent the failure from propagating to a LOM (Loss of Mission).
- Each ESD (failure mode) can be time phased as a unique part of the mission.
- The ESD has the same mathematical result as an event tree.



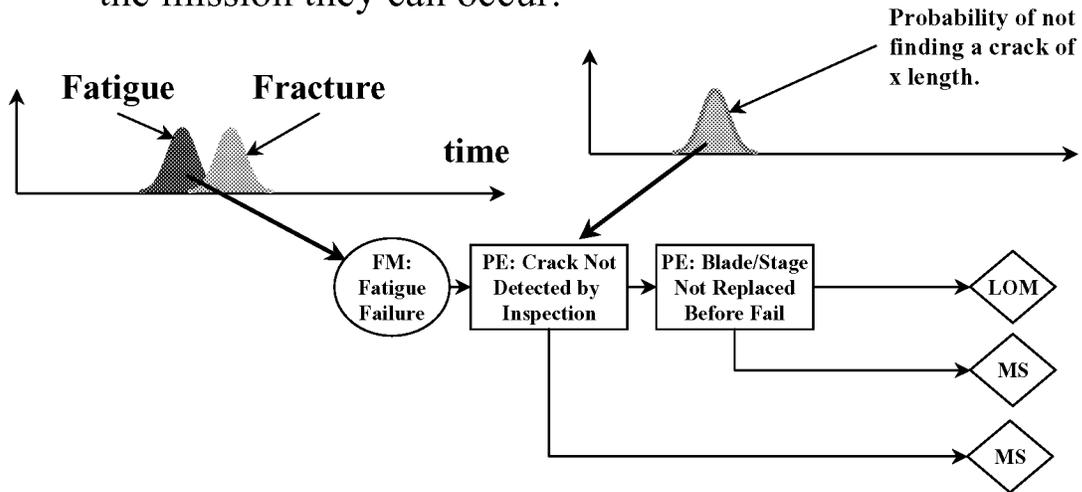
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QRAS -- Assign Probabilities

- Probabilities are assigned to the failure modes and to the mitigating events. Failure modes are quantified as to when in the mission they can occur.



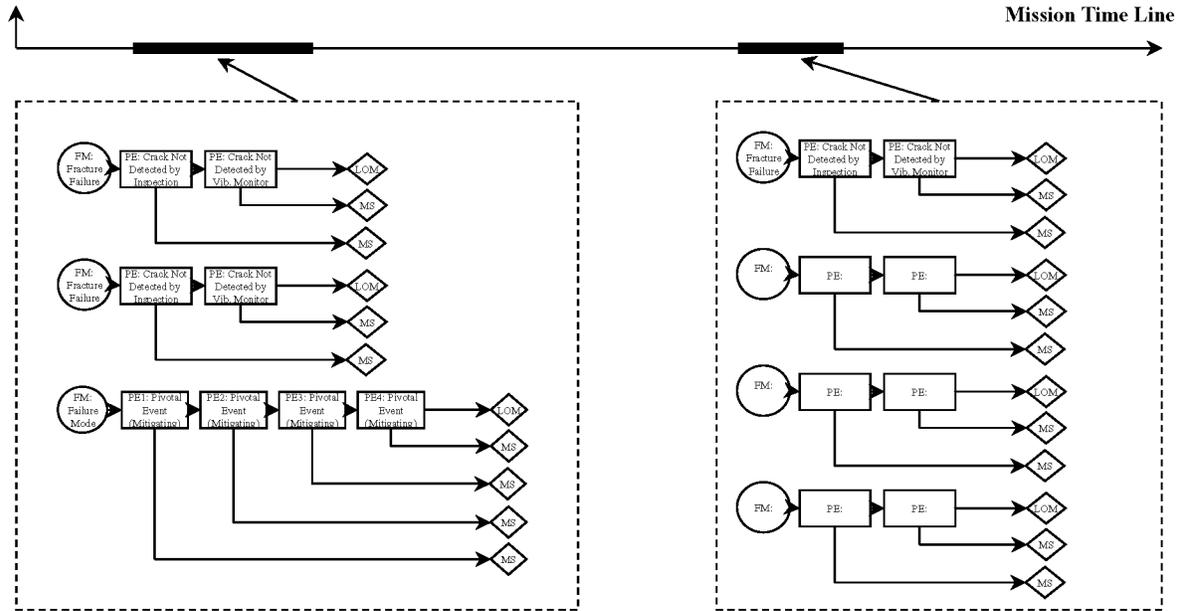


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Combining Event Sequence Diagrams

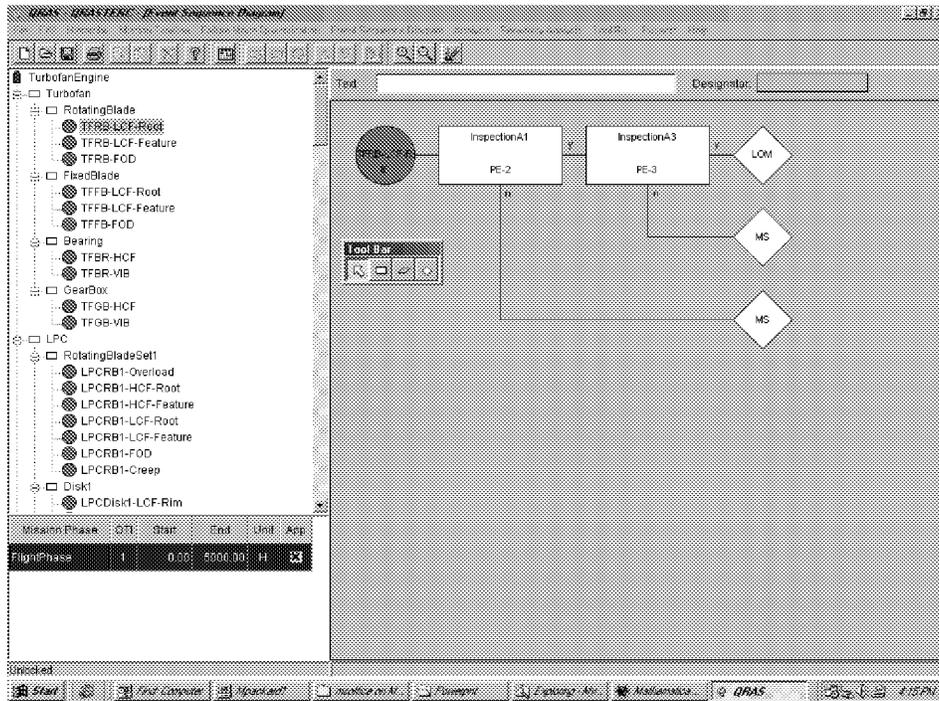




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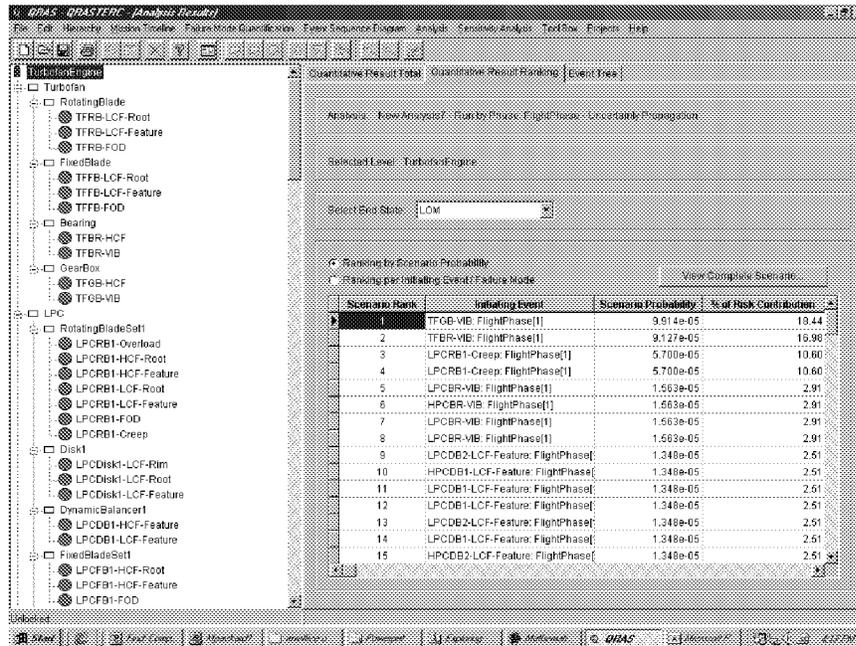




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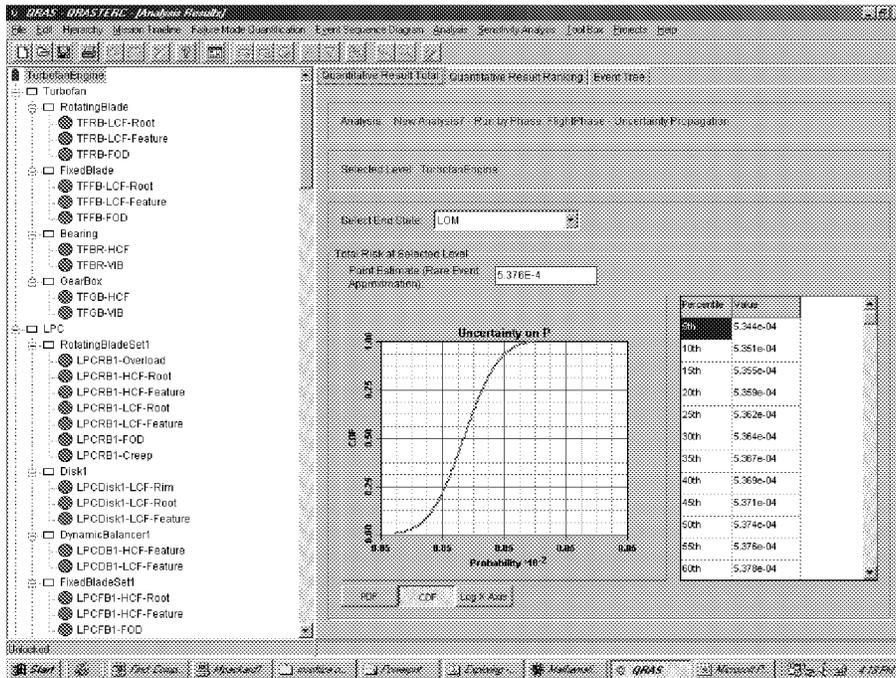




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Analysis Options

Sensitivity Analysis Options [TurbofanEngines]

Sensitivity Analysis Name:

Options

- Modify quantification model of failure mode
- Remove a subsystem
- Replace subsystem with subsystem(s) from another project
- Remove a failure mode
- Add a failure mode
- Modify Event Sequence Diagram
- Change all uncertainty distribution to uniform in selected subsystems

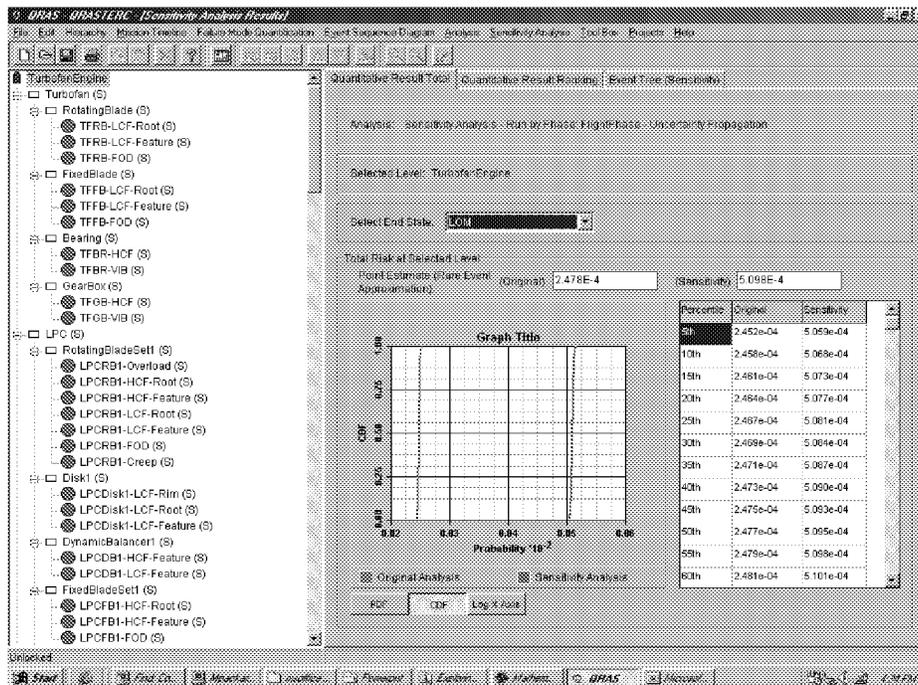
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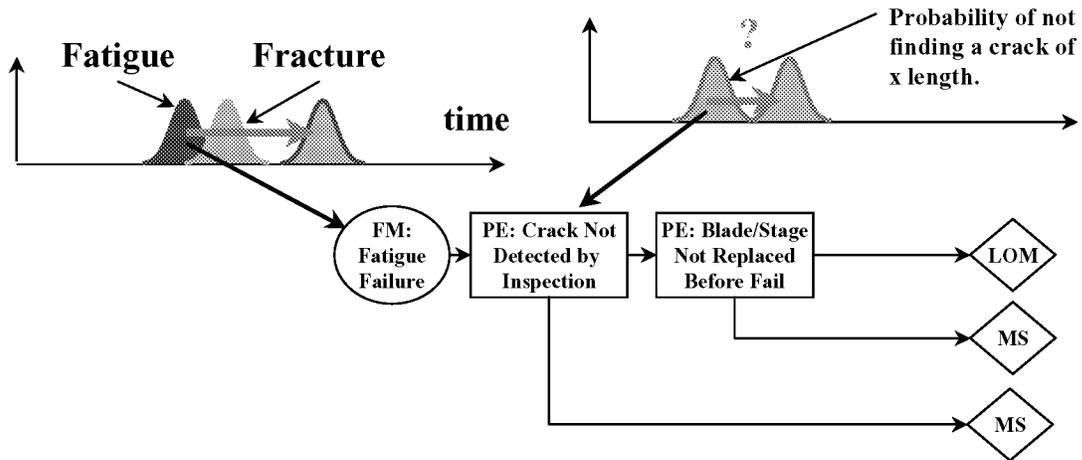


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Limitations

- If fatigue life improved, will inspection interval, change out, effect on other parts in stage change?





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Limitations+

- Statistically independent variables, (change in blade geometry affects another stage?)
- System level failure...affecting multiple components?
- Improved design >>>> Increased power?
- Does not drive reduction in variability
- Individual failure modes probabilities interrelated
- Inspection dependency



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Advantages

- Presentation of systems model/ upgrades to non-technical professionals.
- Quantitative measure of upgrade (assuming relationships between components understood)
- Takes into account, inspection, maintainability, detection, etc.
- Justify maintenance, change out schedule.



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Next Steps

- Develop Standardized Methodology to Characterize Manufacturing Processes
- Develop methodology to evaluate/ optimize probability of detection; replacement options.
- Develop methodology for updating/ calling multiple NESTEM calculations.
- Develop methodology for dependencies.



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Conclusions

- QRAS beneficial for modeling mature design.
- QRAS beneficial for evaluation of upgrades (assuming independence).
- QRAS assists in basic understanding of inspection, POD, maintenance on system reliability.